Industrial Slab-on-Ground Surface Defects

Mortar flaking over aggregates may be related to large top-size aggregates, other issues

by Arthur W. McKinney and Joseph F. Neuber Jr.

Aggregate shading is a mottling of trowel-finished concrete associated with coarse aggregate particles near the slab surface (Fig. 1). Greening and Landgren[1] noted important factors that could cause darkened zones of concrete. These included:

- Localized low water-cement ratio (*w/c*)—paste with a low *w/c* is almost always darker than a similar paste with a high *w/c*; and
- Limited hydration of the ferrite phase (iron compounds) in the cement—unhydrated ferrite phases are blackish-brown, and hydration lightens the color.

It's apparent that compression dewatering due to troweling causes a lowered *w/c* in the mortar above the near-surface aggregate particles, so dark zones result.

Normally, aggregate shading is simply an aesthetic problem that doesn't affect the performance of an industrial slab-on-ground. Recently, however, we have investigated industrial slabs in which aggregate shading is associated with flaking of the mortar layer above coarse aggregate particles. Although an individual mortar flake is a small defect, clusters or a high frequency of flaking might cause an owner to deem the floor surface unacceptable.

We believe the mortar flaking is largely the result of insufficient paste over the large coarse aggregate particles. In this article, we discuss a number of factors that could contribute to inadequate embedment as well as other factors that could result in flaking. Finally, we list possible actions for avoiding the problem.

Damage

While the individual defects are relatively small (Fig. 2) and the adjacent areas are typically sound, we've found that defects can occur in clusters (Fig. 3 and 4). Small bumps may appear on the surface prior to flaking, but that's not always the case. We've also noted that limited craze cracking

Fig. 1: An example of aggregate shading on the surface of a 10 in. (250 mm) thick floor constructed in 2007. The mixture used on this project comprised large aggregate with very elongated top-size particles, nominally 4 x 1 in. (100 x 25 mm). While the unusual aggregate made it a challenge to achieve adequate embedment, flaking of the surface was observed only in a very limited area

Fig. 2: Close-up of typical flaked area on slab placed in 2012. Note that the nearby surface is darkened and exhibits craze cracking. For scale, a U.S. dime is about 0.71 in. (18 mm) in diameter

may occur around a flake (Fig. 2). Recognition of the problem can be both time- and traffic-dependent.

On rare occasions, the problem may be detected by close inspection of the surface during the final hard-troweling process. Although mortar flaking may appear to be similar to slab blistering at this stage, mortar flaking is clearly not the same phenomenon. Flaking is associated with coarse aggregate particles (Fig. 5(a)), but blisters are caused by bleed water or air trapped under a dense, troweled surface. Finally, although flaking has been associated with poor aggregate or alkali-silica reactions (ASR) in some pavements, petrographic analyses of the affected industrial slabs indicate that the aggregate particles below the defects are sound and show no indication of ASR.

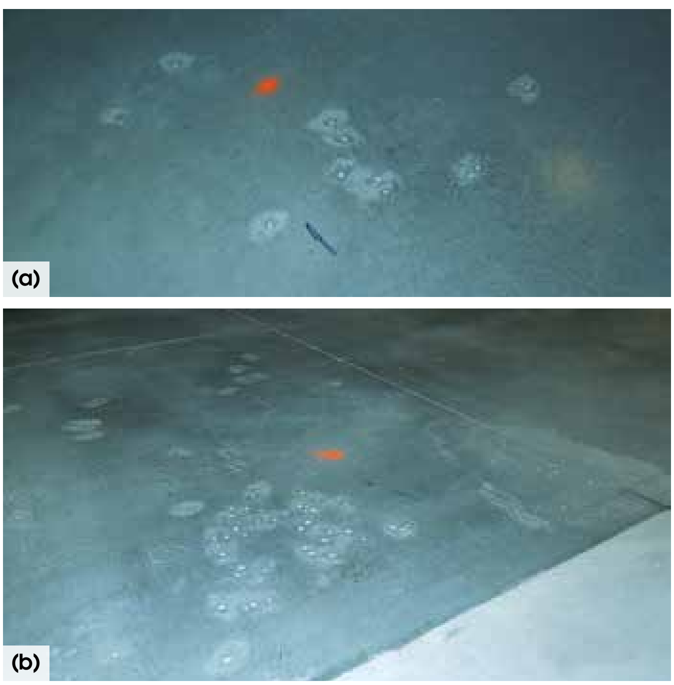

Fig. 3: Mortar flaking tends to develop in clusters: (a) a small cluster; and (b) a more extensive cluster. Repairs require patching the small zones above the near-surface coarse aggregate particles


Fig. 4: Surface distress may occur over a wide contiguous area (in this case, the distress covered about 400 ft² (37 m²)). This surface is shown after about 1 year of service, prior to repair

Basic Causes

Contributing factors could include:

- Insufficient paste, large maximum-size (top-size) aggregate, and poor aggregate grading (insufficient intermediate sizes to stabilize the top-size particles within the matrix—refer to “Mixtures and Materials”). Petrographic evaluations have indicated that the embedment problem is associated with deviations from approved combined aggregate gradations (Fig. 5(a) and (b)); and
- Application of insufficient or mistimed compactive effort relative to the stiffening characteristics of the surface region concrete.

Figure 6 lists the finishing operations for slab-on-ground floors,[2] and it illustrates how the timing of the operations should correlate with the behavior of the concrete as it sets and hardens. Placing and finishing floors to high flatness and levelness tolerances, particularly on large projects, has been enabled by the development and use of modern laser-guided screeds (laser screeds) and pan floats.[3] While these technologies allow very high productivity (Fig. 7), it’s important that the finishers are aware of potential concerns:

- The screed bar may be moved too quickly or the vibration level may not be adequate to ensure that large aggregates are moved below the slab surface. This is a particular problem at the end of a pull of the screed bar, before the machine is indexed to its next position. The vibration will be stopped as the screed bar stops moving, and this may leave a windrow of large aggregates near the surface of the placement. The problem can be worsened if the concrete placed adjacent to the windrow is the first material down the chute of a subsequent concrete truck, as the initial discharge is typically segregated toward the top-size aggregate (Fig. 8).
- Finishers may avoid operations that could reduce flatness. While laser screeds can help finishers achieve high flatness numbers without using bull floats or straight edges, skipping these steps may allow large aggregate particles to remain near the slab surface until the power-floating operations begin. A primary purpose for floating is to: “embed the large aggregate beneath the surface mortar layer”[4] (finishers describe this as “pulling up the mortar” as opposed to pushing down the aggregates). If the finisher waits too long and doesn’t “hit the gap” for using a power float (refer to Fig. 6), it may not be possible to sufficiently embed the large aggregate.
- For large projects, the concrete mixture must have minimal shrinkage to reduce the potential for curling and warping. The top size and coarse fraction of the aggregates are thus typically increased and the overall aggregate gradation must be blended by introducing a

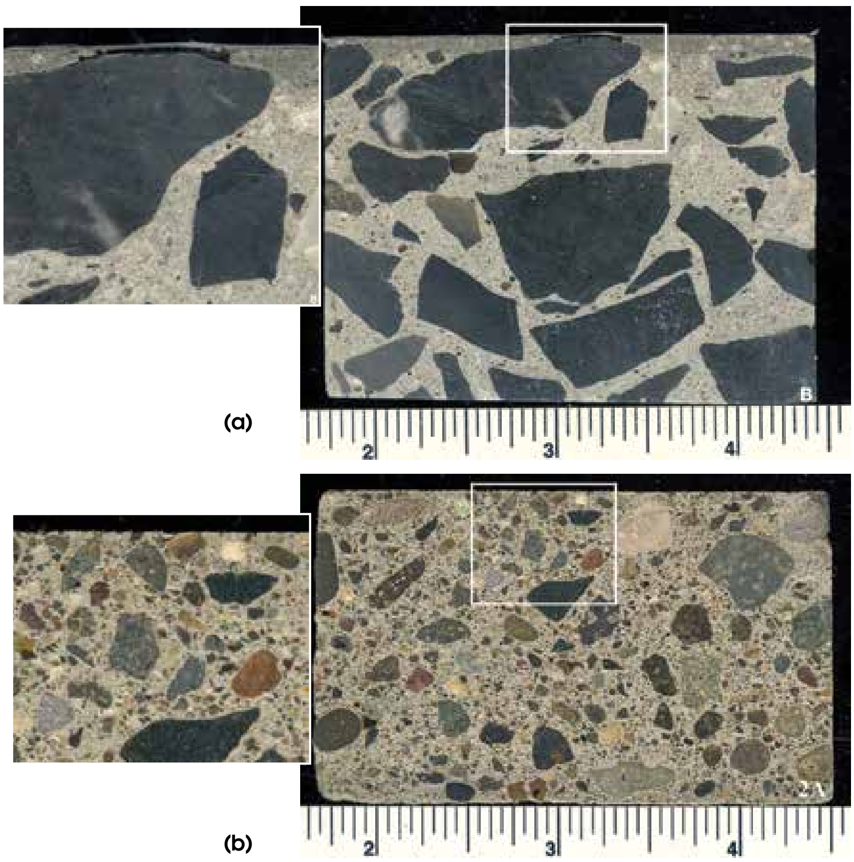

Fig. 5: Cross sections of cores: (a) core taken at a flaked area in a slab constructed with gap-graded aggregate—the thin mortar over the coarse aggregate particle has dislodged (tape was applied to facilitate processing); and (b) core taken from a slab constructed with well-graded aggregate *(images courtesy of Erlin Company, Inc.)*

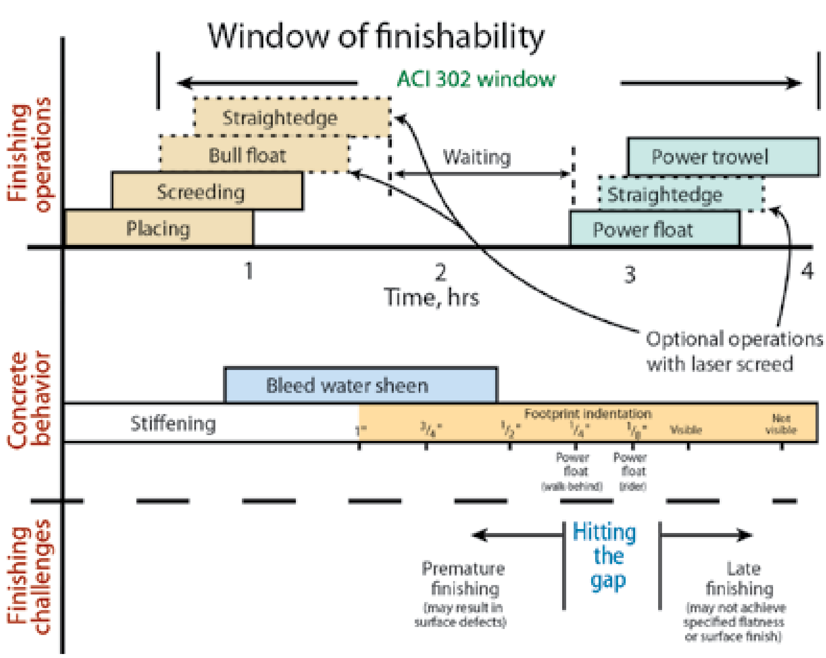

Fig. 6: Finishing operations for a slab-on-ground floor. When a laser screed is used, some traditional operations may not be necessary to achieve a flat and level floor (based on Reference 2) (Note: 1 in. = 25.4 mm)

third aggregate stream to restore the material retained on intermediate sieves. If the mixtures lack the material retained on the No. 4 and No. 8 (4.76 and 2.38 mm) sieves (more generally, the bottom of the coarse aggregate sizes and the top of the fine aggregate sizes), the finishers will have to put more compactive effort into the slab to "pull up the mortar." Recent projects exhibiting mortar flaking have been found to be deficient relative to the intermediate sizes necessary to meet the approved blended aggregate requirements.

Overall, the problem can be seen as an unintended consequence of approaches that provide the industry with the capability of producing a level of quality unattainable under prior technologies. Means, methods, and materials, however, are interdependent and reliable success can best be realized if the performance boundaries are recognized and quality control maintained across the supply chain as well as in the field.

A Challenging Response

From a placing and finishing standpoint, a consistent, predictable concrete mixture is necessary. This is particularly critical on major projects where large daily placements may stress the overall material production and delivery processes. Unfortunately, one implication of the recent problems is that mixtures may be diverging from specifications and lacking critical incorporated materials.

The basic production standard for concrete for industrial floor slabs is ASTM C94/C94M, "Standard Specification for Ready-Mixed Concrete." This, in turn, references ASTM C33/C33M, "Standard Specification for Concrete Aggregates," which refers to ASTM C136, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates."

Section 5.4.2 of ACI 302.1R-04[7] provides guidelines for aggregate grading for mixtures to be used in trowel-finished floors, but the specific

Mixtures and Materials

For slab-on-ground construction, the goal is to have a mixture that has low ultimate shrinkage, yet has an adequate paste fraction to permit proper placement and finishing.

A concrete mixture for a large industrial slab will typically incorporate a high volume of coarse aggregates with a large top-end size,[5] and the aggregate gradation is normally uniform. This allows packing of the aggregates and lowers the ultimate drying shrinkage of the mixture, substantially reducing problems with curling (warping) and cracking.[6-8]

The following specific characteristics are normally required for the mixture:

- Adequate strength, indicated by a minimum modulus of rupture of 570 psi (3.9 MPa);
- Low ultimate drying shrinkage, indicated by 0.050% or less shrinkage measured per ASTM C157/C157M, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete";
- Placeability, qualitatively indicated by a mixture that moves down the chute with little effort and without segregating; is homogenous and will hold its shape; moves easily with a shovel or come along at a slump no greater than 6 in. (150 mm) (achieved using a conventional water reducer [Type A per ASTM C494/C494M, "Standard Specification for Chemical Admixtures for Concrete"]); and exhibits a smooth consistent surface after strike off and bull floating; and
- Finishability, qualitatively indicated by a mixture that sets consistently with placement sequence and time; has sufficient surface mortar to be worked using float, combination, and trowel blades; allows the surface mortar to be blended during the different finishing stages, closing the surface and providing a smooth, consistent finish; and allows sufficient time to perform the required finishing steps with little or no "panic."

To achieve those characteristics, aggregates should conform to ASTM C33/C33M, "Standard Specification for Concrete Aggregates," and they should be of the correct quality, shape, soundness, and cleanliness. While ASTM C33/C33M provides gradations for source materials, it does not establish the combined gradation required for trowel-finished concrete floors. These must be defined in the project specifications, using guidelines in ACI 302.1R-04,[7] for example. Per the ACI document, gap grading should be avoided, and it's particularly important to maintain the midsize material—particles retained on the No. 4 and No. 8 (4.76 and 2.38 mm) sieves. However, we've observed that there are significant economic incentives to divert these mid-range materials to other applications (such as asphaltic cement concrete), and this creates recurring problems for concrete producers.

grading requirements will be spelled out in the contract documents.

ACI 301-10[9] specifically requires that: "Aggregates used in concrete shall be obtained from the same sources and have the same size range as the aggregates used in the concrete represented by submitted historical data or used in trial mixtures." From a quality control standpoint, in-process sampling and validation of the aggregate gradations is somewhat problematic, but changes clearly will occur. The quality of the stone may vary as the quarry operation advances, and normal wear of the crushers and screens used to process the material will cause additional variations. This

Fig. 7: Typical industrial slab finishing steps: laser screed (foreground), bull (channel) floating, check rod, power floating, and power troweling *(photo courtesy of Structural Services, Inc.)*

Fig. 8: The first concrete out of the chute is typically segregated toward the top-size aggregate

suggests that testing should involve multiple samples and tracking of trends.

Even on large projects, it's typical to rely on the ready mixed concrete producer for quality control of materials incorporated into the concrete. Project testing normally concentrates on the concrete mixture as delivered to the site and incorporated into the work. For large projects (placements of 500 to 1000 yd^3/day [400 to 800 m^3/day]), the aggregate stockpiles at the ready mixed concrete plant may be depleted and require ongoing replenishment from the aggregate supplier during a placement. This imposes a very practical time constraint on the producer for sampling and obtaining useful results for quality control. It also requires a higher level of responsibility on the part of the aggregate supplier to maintain quality control on the specified materials as delivered to the ready mixed concrete plant. Variations in the blended gradations may not be apparent in slump tests, and they may not be apparent to the placing crew. As recommended in Annex A1 of ASTM C94/C94M, washout testing can provide an indication of the coarse aggregate content (No. 4 and larger) in a mixture. Conducting on-site washout tests (refer to "Washout Test Procedure") on the delivered concrete could serve as an indicator of changes in the gradations.

None of these tests, however, deal with the question of "dirty" aggregates (Fig. 9). Analysis of the amount of material passing a No. 200 (75 µm) sieve might serve as an indicator of excessive fines on the coarse aggregate, but ASTM C136 may not accurately determine this quantity. ASTM C117, "Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing," should provide a more reliable result.

Avoiding the Problem

From a finisher's perspective, mortar flaking is a difficult problem. If identified during construction, corrective action can be taken by ensuring that coarse aggregate is properly embedded. Even though it's possible to make repairs to isolated defects, if recognition of the problem is delayed, it's likely these repairs will be visually apparent. The best alternative is avoidance. Potential keys to avoidance include:

- Maintain an adequate mortar fraction of 0.53 to 0.55;
- Verify that gradations are consistent and comply with the project documents. Specifically, use an independent testing agency to conduct periodic sieve tests of the aggregate stockpiles and washout tests of delivered concrete and thus check that intermediate aggregate sizes are in blended aggregates;
- Check to ensure that dirty or unwashed aggregates are not used;

Fig. 9: Coarse aggregate particles coated with fine materials may interfere with bond and thus contribute to flaking

Washout Test Procedure

We understand that the following procedure has been successfully used to verify the aggregate grading in a fresh concrete sample.[10] After removing the paste component of the concrete, a particle-size analysis is performed on the washed fine and coarse aggregates in accordance with ASTM C136, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates."

1. Obtain a representative sample of concrete per ASTM C172/C172M, "Standard Practice for Sampling Freshly Mixed Concrete," and evaluate the slump in accordance with ASTM C143/C143M, "Standard Test Method for Slump of Hydraulic-Cement Concrete."

2. Place the tested (slumped) concrete in a sample container that is a wire basket similar in size to a basket used to conduct specific gravity tests per ASTM C127, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate," but with No. 4 (4.76 mm) mesh. Transfer the loaded basket to a clean, 5 gal. (19 L) pail. Run clean water through the basket while gently agitating the basket to allow cement paste and aggregate particles smaller than the sieve openings to pass into the pail. Do not overfill the pail.

3. Move the basket and the retained material to a second clean pail and run water through the basket while gently agitating the basket to remove cement paste. Repeat with a third pail if necessary. Stop when the water runs clear.

4. Set aside the sample container and washed sample (material retained on a No. 4 sieve).

5. Decant the material remaining in the pails into a No. 100 (0.149 mm) sieve. Rinse pails with clean water and decant into the No. 100 sieve until the water runs clear.

6. Recombine the samples retained in the sample container (basket) and No. 100 sieve. Transport the combined sample to a testing laboratory, and conduct a sieve analysis per ASTM C136.

7. Graph the washout sieve analysis results with the specified gradation for the concrete mixture (for ease of interpretation).

- Recognize that strategies for achieving low shrinkage and flatness are limited by finishability; and
- Consider use of a walk-behind trowel equipped with float shoes as the first finishing operation after screeding.

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10. Personal communication with Russell Neudeck, Quality Assurance Manager, The Haskell Company, Jacksonville, FL.

Note: Additional information on the ASTM standards discussed in this article can be found at www.astm.org.

Selected for reader interest by the editors.

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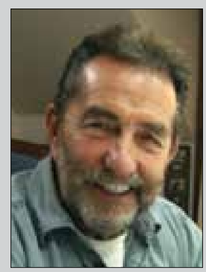

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